Flexural strength of fibre reinforced concrete in relation to the angle of magnetically orientated fibres

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Abstract. This paper focuses on high-performance fibre-reinforced concrete and its flexural strength concerning fibre orientation. The orientation is provided by a fully controlled special device. This device can align the fibres in fresh concrete using a magnetic field. The specimens are inserted into the device at different angles to ensure different fibre orientations concerning the longer side of the sample, which corresponds to the direction of the main tensile stresses. Specifically, angles of 0 °, 30 °, 60 ° and 90 ° are tested and compared with each other and with reference specimens that are not exposed to a magnetic field. All samples are measured by a non-destructive method. This method was developed in our previous research and is based on measuring the quality factor Q of a measuring coil using an impedance meter. The samples are inserted into a measuring coil connected to an impedance meter. Flexural strength is obtained from the results of a three-point bending test. All samples are tested until complete failure.

1 Introduction

High-Performance Concrete (HPC) is a modern cement-based composite characteristic with high durability and high compressive strength [1]. The combination of HPC and steel fibres creates (HPFRC) a material with even better mechanical properties. Steel fibres increase tensile stress and enhance toughness [2]. The position and orientation of fibres plays important role in mechanical properties. The most efficient use is to place and align fibres in direction of the main tensile stress [3].
The fibres can be aligned, for example, either by the way the mixture is casting or by the action of a magnetic field. In the first case, the fibres are aligned in the direction of the fresh concrete flow and this method is highly dependent on, the rheology of the fresh mixture, the shape of the mould and the size of the fibres [4], [5]. The major disadvantage of this way of orientation is that it can never be fully controlled. The second option aligning fibres with a magnetic field can be used just for fibres from ferromagnetic material [6]–[11]. This option can be fully controlled but is highly dependent on the shape of the magnetic field (fibres are aligned always in the same direction with agentic field lines) and the rheology of fresh concrete (the magnetic field has to be strong enough to overcome the resistance of cement matrix [12].
In this paper, the second method of orientation with a magnetic field is used. The special device designed and tested in our previous research is used to obtain the required fibre orientation. This technology of magnetically orientated fibres has great potential in industrial use, where it can decrease human sources and increase automatization of whole concrete prefabricates, which is perfectly fulfilling the concept of construction 4.0 [13].
Because the CT scans or X-ray are an expansive method of detection of the position and orientation of fibres, we have developed the non-destructive inductive method for a comparative measure of the fibre's orientation. This non-destructive method is time-independent and can be even used for non-harden specimens. In previous research, this method has been proven as a fast, reliable, and low-cost way how to detect the orientation of [14], [15].

2 Material and methods

2.1 Manufacturing of specimens

Table 1. shows the mixture design of the HPFRC, this mixture is combined with 1,5 % of the volume of Weidacon FM high-strength steel fibres with a length of 13 mm and diameter of 0,15 mm, which corresponds to an aspect ratio of 87. The mixture was prepared in a 5l pan mixer. At first, all dry constituents were mixed for 3 minutes, then water with a high-range water-reducer (HRWR) was added and mixed for additional 10 minutes for the full activation of the used HRWR. Afterwards, steel fibres were added to the running mixer, to eliminate fibre clustering, which took 5 more minutes. Special plastic moulds must be used because of the magnetic field. The fresh HPFRC was cast by hand into the centres of

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these plastic moulds to let the material flow into the whole volume. The moulds had dimensions of 40 mm × 40 mm × 160 mm. These dimensions were chosen because of the typical dimensions of testing specimens according to the standards EN 12390 -1 and the dimensions of special equipment generating a magnetic field.

Table 1. The mixture composition.

Constituent	Rel. weight	kg/m^3
Cement 42.5 R	1.000	692.7
Water	0.281	194.5
Silica fume	0.110	76.2
Silica flour	0.280	194.0
High-range water-reducer	0.057	39.5
Silica sand 0/1.2 mm	0.820	568.0
Silica sand 0/4.0 mm	0.940	651.1

All filled moulds prepared for magnetic orientation were closed from the top and immediately subjected to the magnetic orientation process. Exposure time to the magnetic field is 5 seconds. It is important to assure exposition to the magnetic field as soon as possible as the fresh mixture has suitable rheology so the magnetic field can overcome the matrix's resistance against the fibre rotation [12].

Fig. 1. The device generates a magnetic field to align fibres in fresh concrete.

The fibres have been oriented with a special coil device using a magnetic field (Fig.1.). It consists of a coil generating the required magnetic field and a plastic conveyor. The same device has been designed in previous research. The device is constructed for specimens with cross-sections up to 100 mm x 100 mm and the parameters are as follows. The coil has 215 turns of copper tube with a diameter of 6 mm/4 mm (outer/inner diameter) with cooling water circulating inside the coil winding. In total 5 compensating capacitors are connected in parallel to the coil, each of them having a capacity of 300 μF. The voltage is 300 V and is provided by a step-down autotransformer connected to a 400 V mains line. The current passing through the inductor is 150 A and generates a magnetic induction of 100 mT. The alignment of fibres at different angles is assured with a special holder (Fig. 2.). In total five series of specimens have been produced, specimens marked as 0° have fibres aligned parallel to the long side of specimens, and the ones marked as 30° have fibres oriented at the angle of 30° between fibres and the long side of the specimen and so on for other two angles 60° and 90°, where 90° means the perpendicular orientation of fibres to the specimen's long. These marked as N are reference specimens and they are produced conventionally without exposition to the magnetic field.

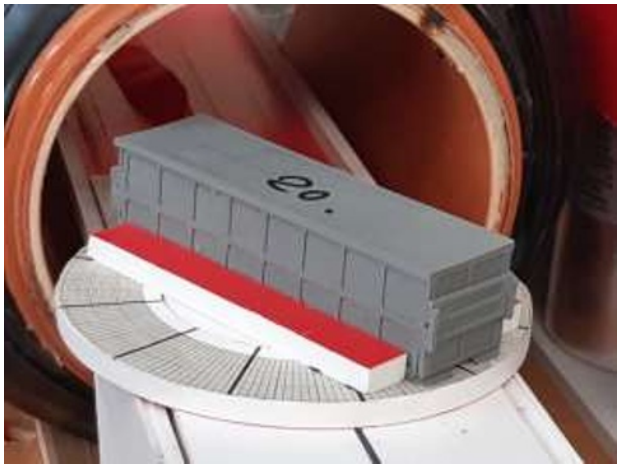

Fig. 2. The placed specimen in the holder at different angular rotations.

2.2 Testing

Specimens were demoulded after 24 hours from prefabrication and afterwards measured with the non-destructive method. The non-destructive method uses a measuring coil with an inserted specimen, the measured value is quality factor Q for evaluating the fibre orientation [14]. The measurement setup of Q factor consists of an impedance meter HIOKI IM3536 and a coil with 28 turns of a copper wire with a cross-section of 1,8 mm^2. The specimens are inserted one by one inside the measuring coil and the value of Q factor is read. The measuring coil can measure specimens with a maximum cross-section of 40 mm × 40 mm. The measuring is performed on the frequency range from 1 kHz to 6 MHz where Q shows the highest sensitivity for this particular setup. The specimens with fibres that were more aligned to the axis of the measuring coil (in our case 0°) have a lower value of Q factor than specimens with fibres aligned perpendicularly to the axis of the measuring coil (90°). The peak Q value is used for comparison between the specimens. It is important to mention that the measurement is comparative, and the absolute value is dependent not just on the orientation of the fibres but also on the size of the specimen (the volume of the fibres) and the measuring coil's parameters. Only specimens with the same percentage of fibre volume can be compared with each other [14].
Subsequently, after the non-destructive measurement, the specimens were kept for 27 days in a dry room

environment at 20° C and after this time, they were tested using a three-point bending experiment. The test was done using a hydraulic loading machine with a deformation control of 0,1 mm/min. The total span was 100 mm, and the loading point was in the middle. All specimens were tested until to a minimum of 3 mm of displacement. The fragments were then subjected to compressive strength tests.

3 Results

The orientation of the fibres was already visible to the naked eye after demoulding for fibres close to the surface (Fig.3.). Fig.4. shows the measured quality factor *Q* and flexural strength. The number signs the angle between the fibres and the long side of the specimens. Specimens marked as N are reference specimens, which are not exposed to the magnetic field. Specimens with fibres aligned parallel to a long side of a specimen (0°) have higher flexural strength because the fibres are orientated in direction of main tensile stress, and have a lower value of *Q*. As in the previous research [14], the results show the non-destructive measuring method very well corresponds to the mechanical properties, concretely to the flexural strength. The average values of Q are 26, 30, 50, 94 and 32 for 0°,30°,60°,90° and N (non-oriented specimen), respectively (). The values of flexural strength are 13 MPa, 10 MPa, 7,5 MPa, 7 MPa and 11 MPa for 0°,30°,60°,90° and N, respectively. As mentioned above the specimens with oriented fibres in the direction of the long side show the highest strengths and the lowest *Q*. The reference specimens exhibit similar mechanical properties to specimens with fibres oriented at an angle of 30°. However, it is important to underline that the fibre orientation of the reference specimens is quite dependent on the mould dimensions. If the mould is smaller and narrow the fibres tend to orient themselves when the mixture is placed in the moulds. However, if the mould is larger, the randomness of the fibres can be expected to be greater, and their average orientation will be probably less than 30°.

Fig. 3. The unmoulded specimen with aligned fibres at the angle of 30 °.

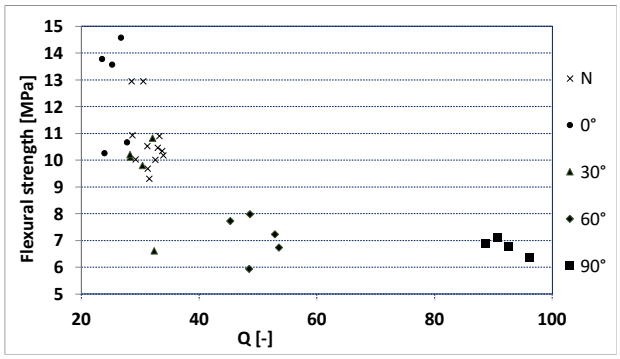

Fig. 4. The Q factor and flexural strength dependency.

Fig.5. – Fig.9. show results from the three-point bending test. The hights peaks show 0° specimens and the lowest one 90°. As can be seen from the diagrams, specimens with higher orientation angles (60° and 90°) are not only unable to withstand lower loads but also show significantly lower residual strength after exceeding the maximum stress. Residual strength is essential for the redundance of the structures, and it is important to consider the orientation of the fibres. On the remaining fragments after the bending test, the compressive strength was tested. The average values are 67 kN, 74 kN, 74 kN, 64 kN and 82 kN for 0°,30°,60°,90° and N, respectively. Although the values may seem quite different, it is important to keep in mind that tests have been performed on fragments. The effect of fibre orientation on compressive strength has not been confirmed.

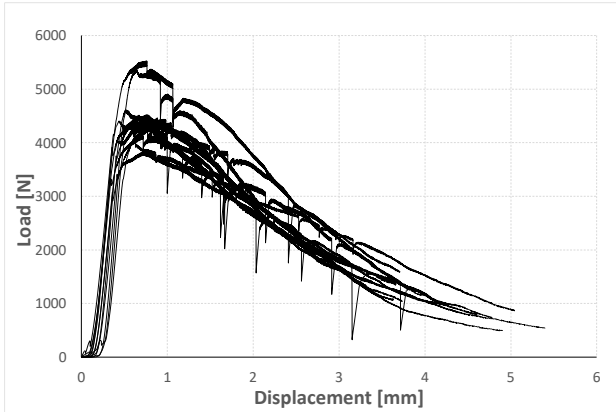

Fig. 5. Load-displacement diagrams – reference specimens.

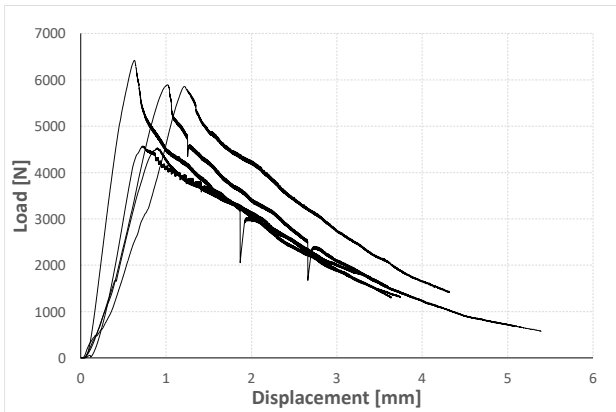

Fig. 6. Load-displacement diagrams – specimens with orientated fibres at an angle of 0 °.

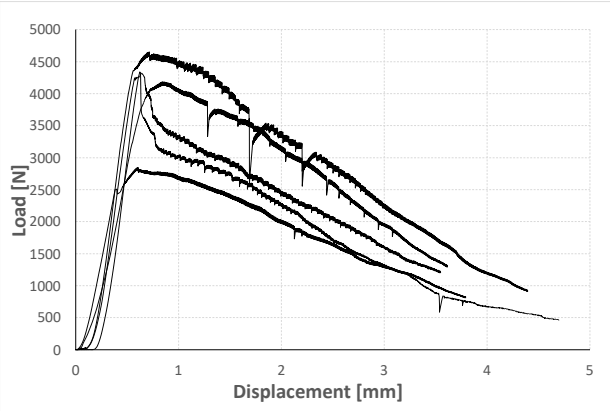

Fig. 7. Load-displacement diagrams – specimens with orientated fibres at an angle of 30 °.

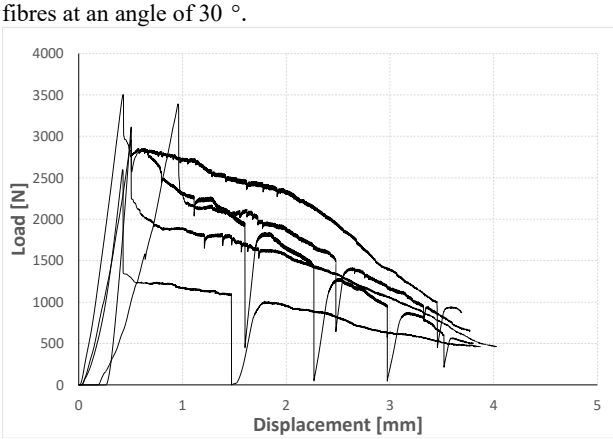

Fig. 8. Load-displacement diagrams – specimens with orientated fibres at an angle of 60 °.

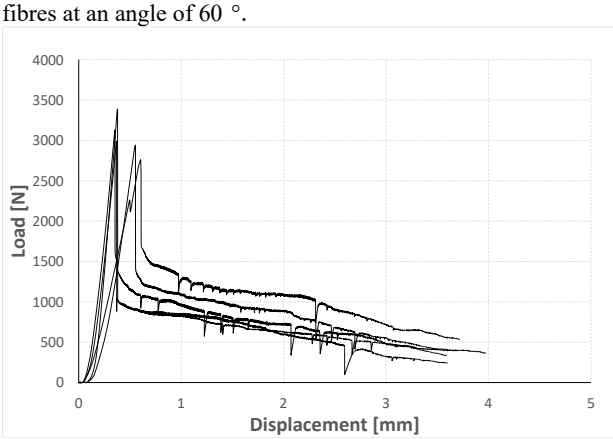

Fig. 9. Load-displacement diagrams – specimens with orientated fibres at an angle of 90 °.

4 Conclusion

In this paper, the dependency of flexural strength on fibre orientation is presented. The orientation of fibre is assured with the special device generating the magnetic field. The flexural strength increases its value by 2 %, 40 % and 80 % for the angle of fibres 60°, 30° and 0°, respectively, in comparison with fibre angle 90°°, where 0° is in direction of the main tensile stress. The results from the non-destructive measurements, which were taken before the destructive tests, showed a very good correlation with the results from the destructive tests. The average values of Q are 26, 30, 50, 94 and 32 for 0°,30°,60°,90° and N (non-orientated specimens), respectively. The values of flexural strength are 13 MPa, 10 MPa, 7,5 MPa, 7 MPa and 11 MPa for 0°,30°,60°,90° and N, respectively. The assumptions have been confirmed, specimens with fibres more oriented in the direction of the main tensile stresses can carry more loads and the non-destructive *Q* measurement method works and correlates very well with the flexural strength results.

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